Cassini Orbit Determination Operations Through the Final Titan Flybys and the Mission Grand Finale: (February 2016 - September 2017)

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Flying Cassini Through the Grand Finale: Prediction vs. Reality

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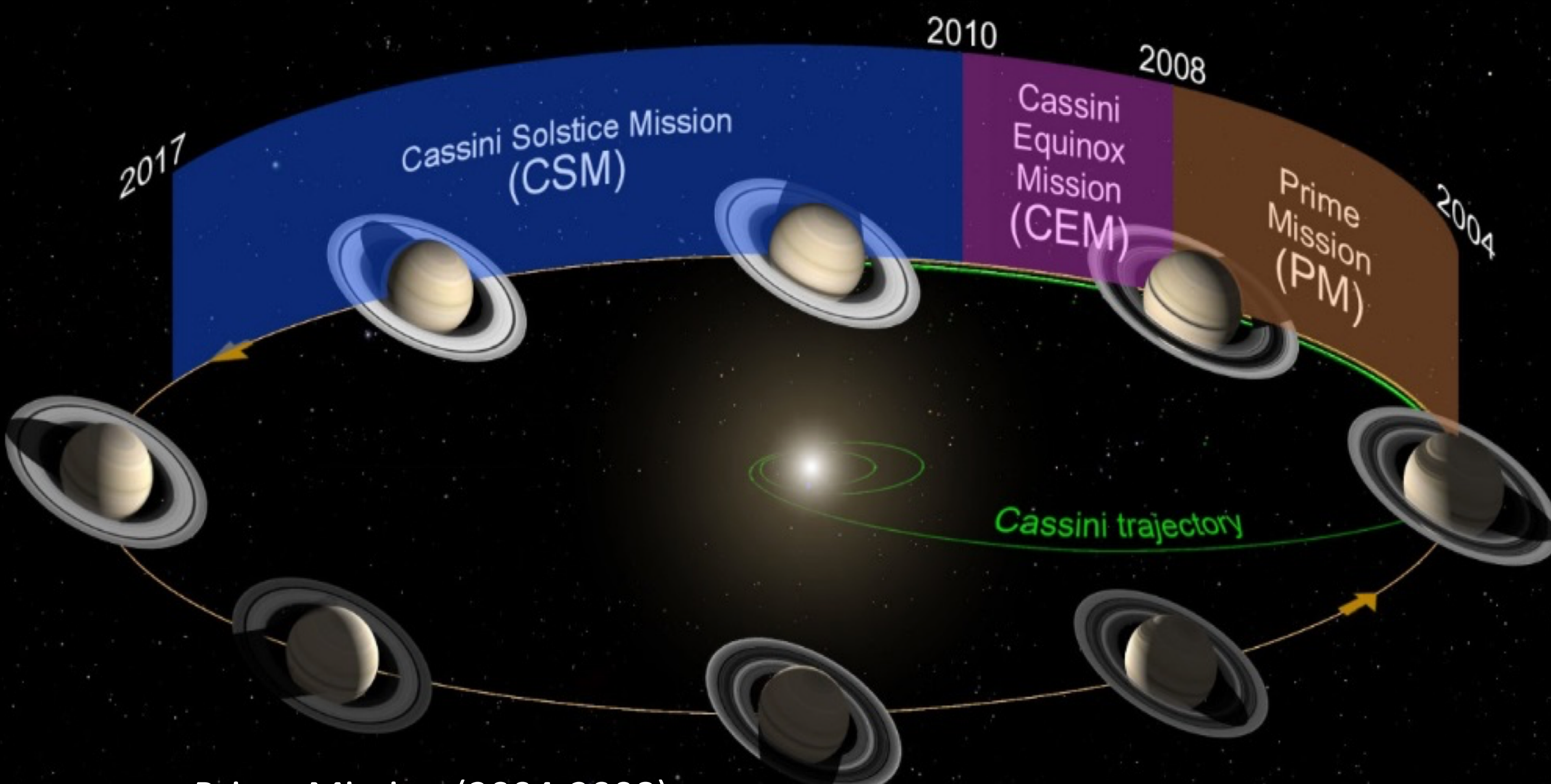
Overview

- An overview of the Cassini Mission
- Navigating the Last Year and a Half of the Mission
  - Highlights of Recent Changes
  - The Last Ten Titan Flybys: How Did We Do?
  - Stellar Occultation by Enceladus
  - Epimetheus Flybys: getting an unexpected nudge
- Navigating the Grand Finale
  - Maneuver challenges and flight path control of the first 18 revs
  - Orbit determination challenges and the last five revs
- The morning of the Grand Finale
- Final remarks

CASSINI MISSION JPL

A Brief History of Cassini

NASA

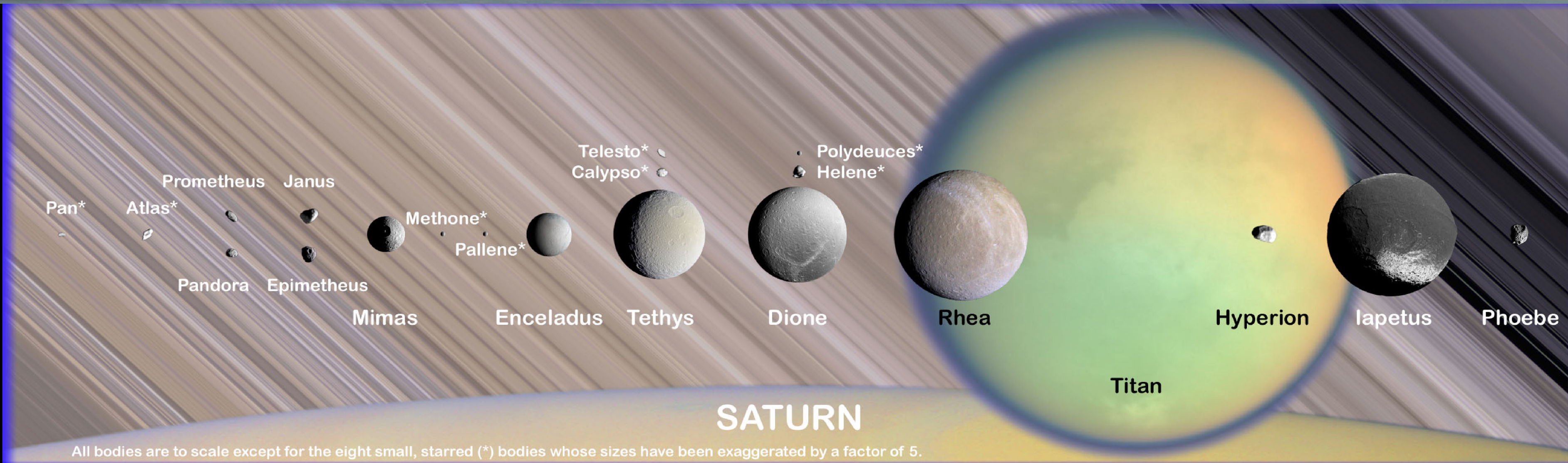


- Prime Mission (2004-2008)
- Equinox Mission (2008-2010)
- Solstice Mission (2010-2017)

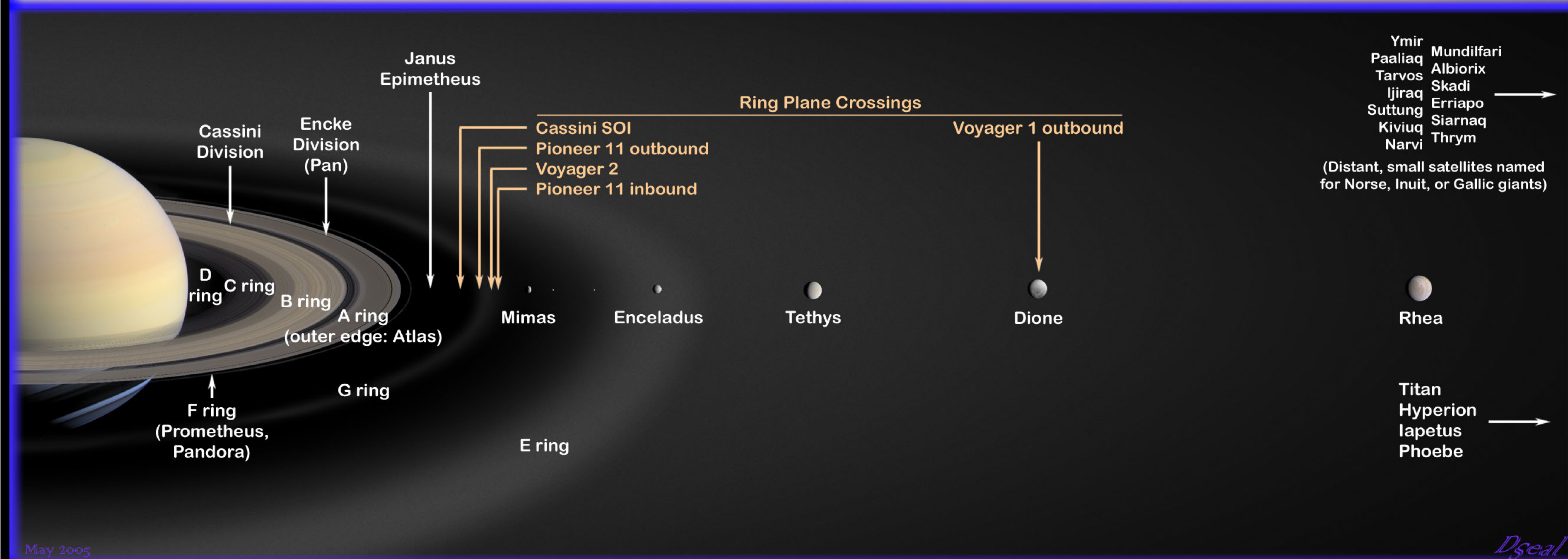
Nov '02 | Aug '09 | May '17 | May '25 | Abr '32

Cassini Mission JPL

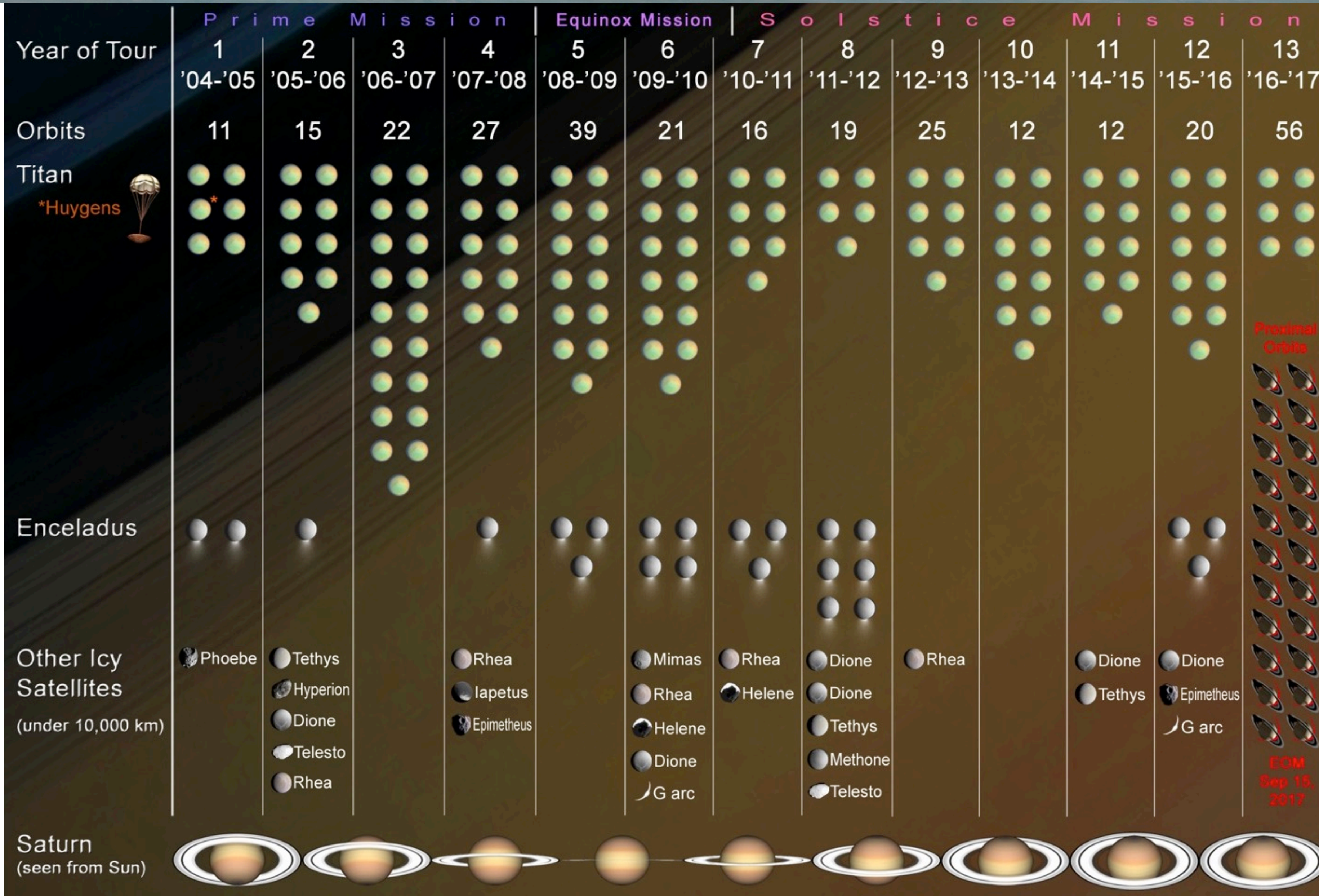
The Saturnian System



All bodies are to scale except for the eight small, starred (*) bodies whose sizes have been exaggerated by a factor of 5.

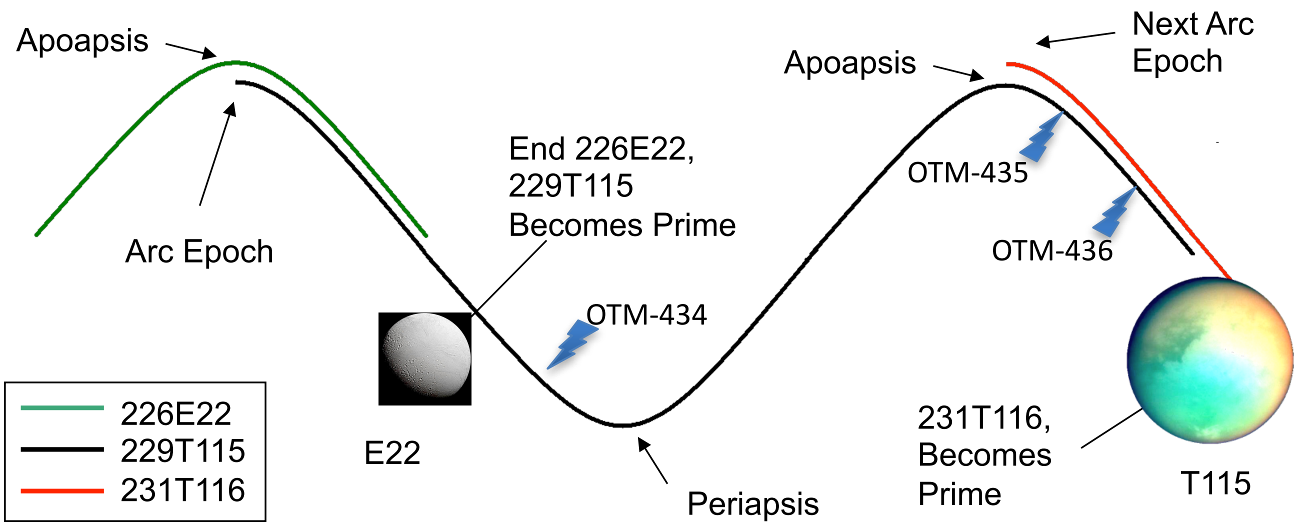


The Cassini Mission



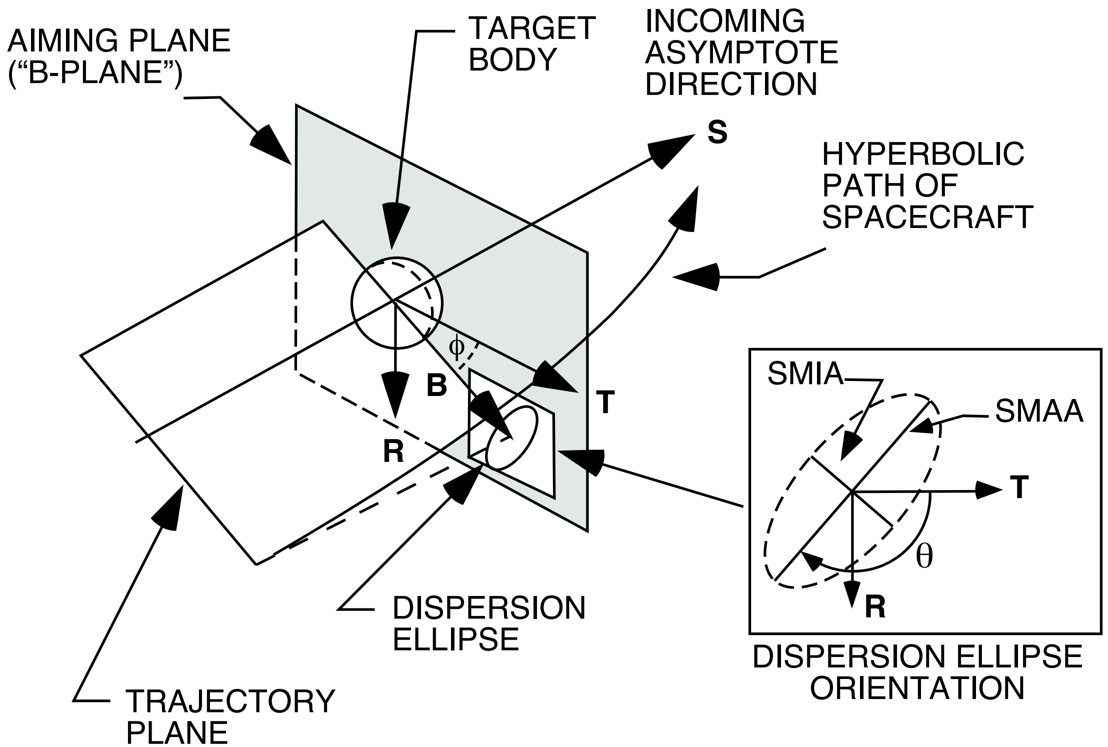
Navigation Operations Structure

- The concept behind the Navigation team is to return the spacecraft to the reference trajectory for targeted flybys (or predetermined control points).
- This is implemented by:
  - Estimating the spacecraft trajectory and associated parameters with covariance
  - Use this knowledge to compute trajectory correction maneuvers
- The navigation analysis is divided temporally into segments focused on a particular targeted encounter, referred to as an ‘arc’.
- Three maneuvers between two encounters: two deterministic, one statistical.

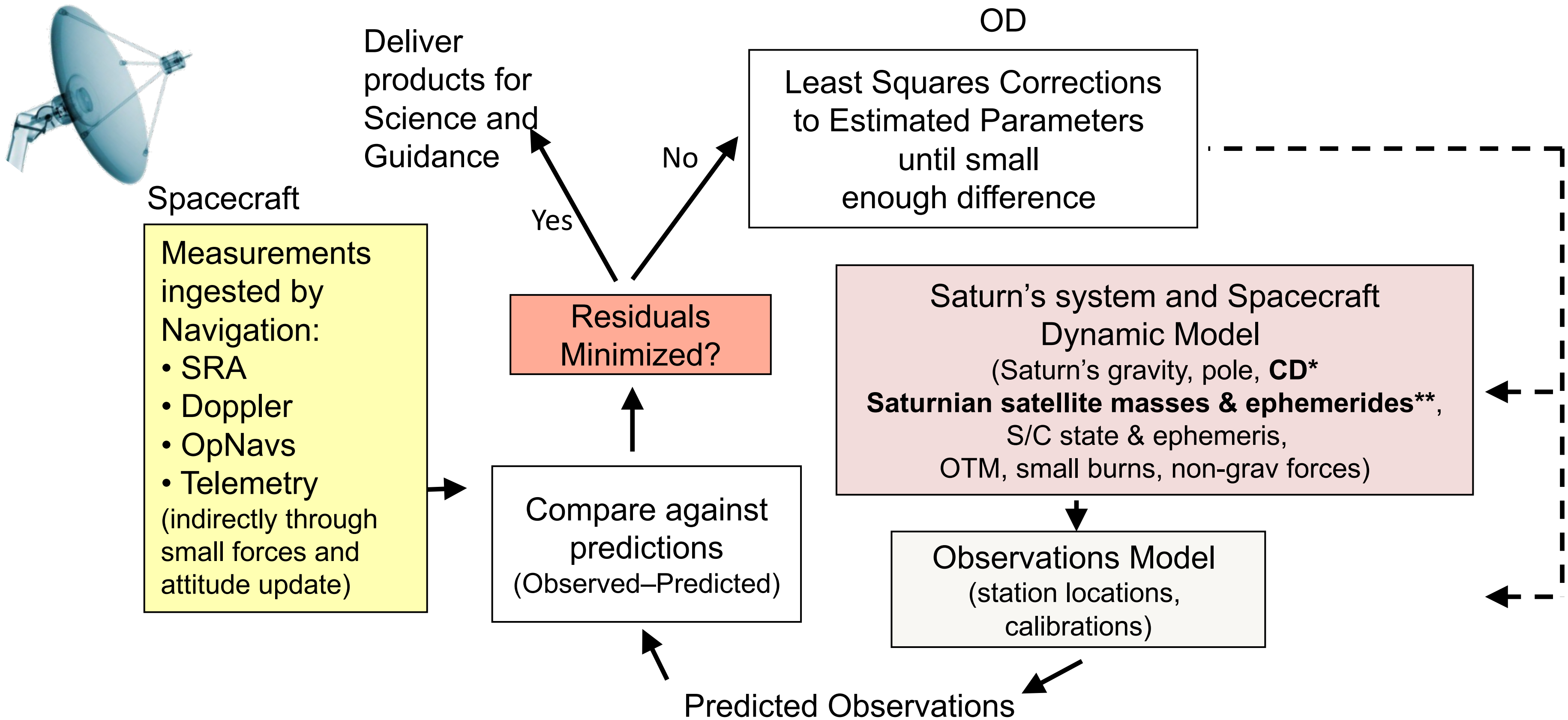


Orbit Determination Process

- The OD performs three distinct tasks for a given arc:
  – Covariance study to look at upcoming dispersion, flyby accuracy prediction.
  – Operations during the given arc.
  – Arc reconstruction to provide most accurate ephemeris, enhance science data reduction.
- Maneuvers typically targeted to “B-plane” of the next flyby.
- The state and covariance produced in the OD process is mapped forward to the B-plane of each encounter within an arc.



Navigating the Last Year and a Half



- Error contribution from Saturn ephemeris, and Earth platform parameters is assessed via including their model parameters, with covariances, in the filter as consider parameters. Saturnian satellites also considered during the Grand Finale.
- Once a converged solution is obtained, interface products are delivered to the Maneuver team for the upcoming OTM design update.

The Last Ten Titan Flybys

- We characterize the navigation performance in terms of targeted encounter accuracy.
  - Each encounter 3D error: difference between the pre- and post-flyby state coordinates at flyby.
  - The 3D error sigma: Mahalanobis distance, or scale factor for the error ellipsoid encompassing the miss.
  - Probability of better solution: probability of lying within the scaled 3D covariance ellipsoid.
  - If the modeling is realistic, we expect the post-flyby B-plane solution to lie within the covariance of the pre-flyby solution.

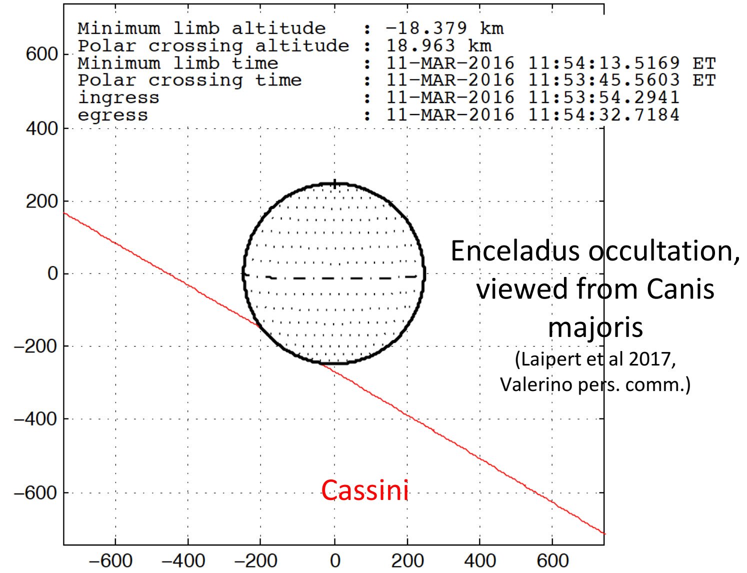
Target	Date	Altitude (km)	3D error (km)	3D sig	Prob. of better solution (%)	Comment
T116	01-Feb-16	1398	2.29	4.8	100	Sat375
T117	16-Feb-16	1018	0.35	2.2	81	
T118	04-Apr-16	990	0.41	0.9	17	
T119	06-May-16	969	2.44	5.8	100	
T120	07-Jun-16	975	1.06	2.9	96	Sat389 + Saturn
			1.17	7.7	100	System estimated
T121	25-Jul-16	975	0.77	2.8	94	
T122	10-Aug-16	1698	1.11	0.5	3.3	
			0.20	0.8	11	
T123	27-Sep-16	1775	0.14	1.6	53	
T124	13-Nov-16	1585	0.37	1.2	29	Last RSS flyby
T125	29-Nov-16	3158	0.33	0.3	0.8	
			0.12	1.1	24	
T126	22-Apr-17	1581	0.32	3.4	99	

- First half of 2016 had large misses at Titan, especially for T116, T119 and T120.
  - Coincident with use of an Saturn pole model including trigonometric terms instead of only linear terms – less accurate.
- The Saturn system’s parameters were put back in the estimated parameters list with looser a priori uncertainties (Boone et al. ISTS 2017), until the Grand Finale.

NAVIGATION CHALLENGES BEFORE THE GRAND FINALE

Stellar Occultation by Enceladus

- In March 2016, a stellar occultation by Enceladus and its plume impacted the navigation activities associated with the design of OTM-443.
- The observation geometry required capturing a plume occultation at Enceladus' south pole.
- Margin of error: 15-40 km.

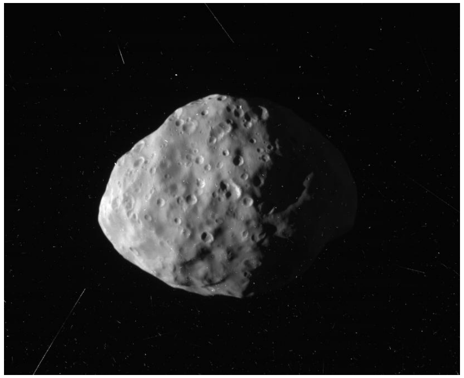


- Since the last control point for this activity was the T117 clean-up maneuver OTM-443, uncertainties at data cutoffs for the prime and backup maneuver opportunities were mapped to the occultation time and examined.
- In mid-Feb 2016, the team decided to forego the prime maneuver and perform the backup.
  - The uncertainties dropped a significant amount, more than half, by waiting for the backup maneuver data cutoff since more data could be processed to resolve the Titan flyby.
  - Fortunately, the cost of possibly missing the maneuver altogether dropped from 0.5 m/s to about 150 mm/s.
- In the end, the occultation was successful with a polar crossing altitude of 24 km, and 30 seconds of star occulted by the plume.

Epimetheus Flyby: unexpected nudge

- The T125 flyby brought the trajectory's periapse to the edge of the F ring.
  - Such proximity allowed for imaging Epimetheus and Janus.
  - Considered as "rocks" and thus their point mass gravitational perturbation on the spacecraft was not previously modeled.

Epimetheus



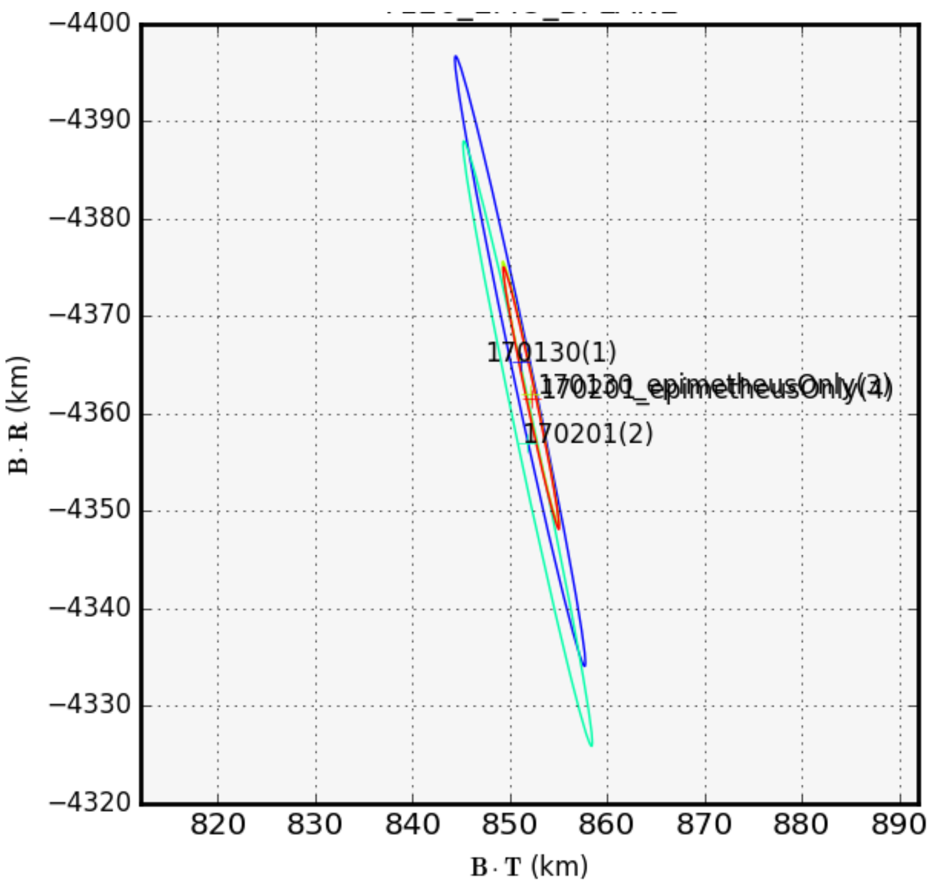
- On January 30th 2017: Epimetheus flyby, at 3567 km.
  - Significant Doppler signature pointing to discrepancies between the pre and post-flyby orbit solutions, and a shift of almost 10 km on the T126 B-plane.

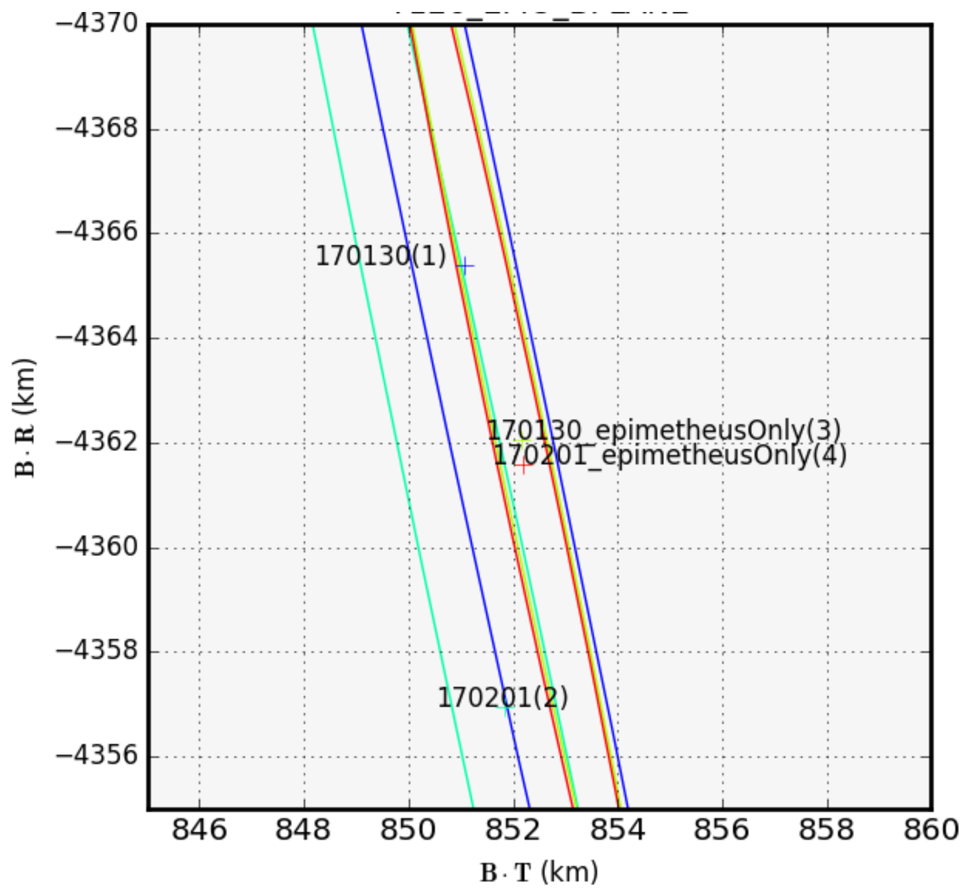
- Hints into dynamical mis-modeling:
  - Spacecraft thrusting force to counter a wheel turn right before periapse for science observations estimated 2 mm/s instead of 0.25 mm/s, but the post-bias telemetry agreed well with the predicted values.
  - The OD solution showed significant corrections to the Saturn gravity field harmonic coefficients, J4 and J6, estimating them 3.5 sigma higher.

- The OD team double checked with back of the envelope calculations before more high fidelity simulations, and updated the OD software.
  - $\Delta V = \frac{2\mu V_\infty}{\mu + r_p V_\infty^2}$, indicating a gravity assist Delta-V on the order of a couple of mm/s.

Epimetheus Flyby: unexpected nudge

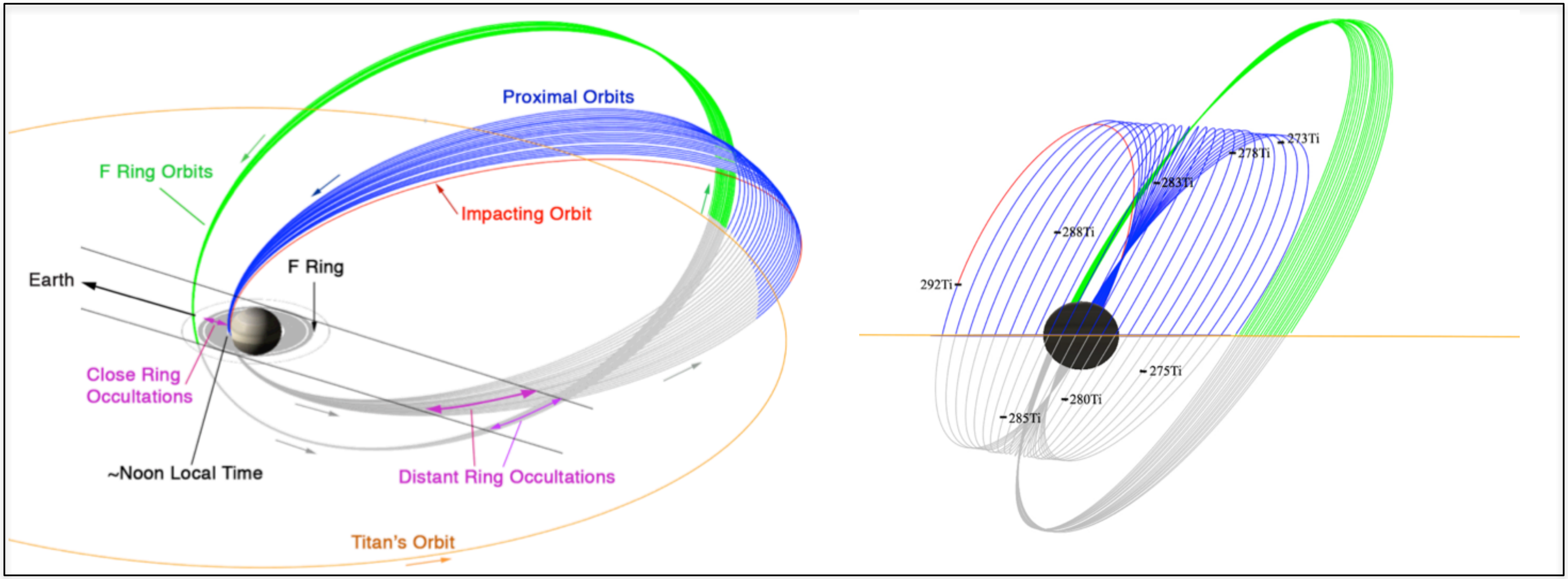
- OD solutions mapped to the T126 B-plane, with and without Epimetheus gravity modeled.
  - Solutions with Epimetheus agree well
- Solutions zoomed in on the right.





THE GRAND FINALE FROM A FLIGHT PATH CONTROL PERSPECTIVE

Cassini Grand Finale



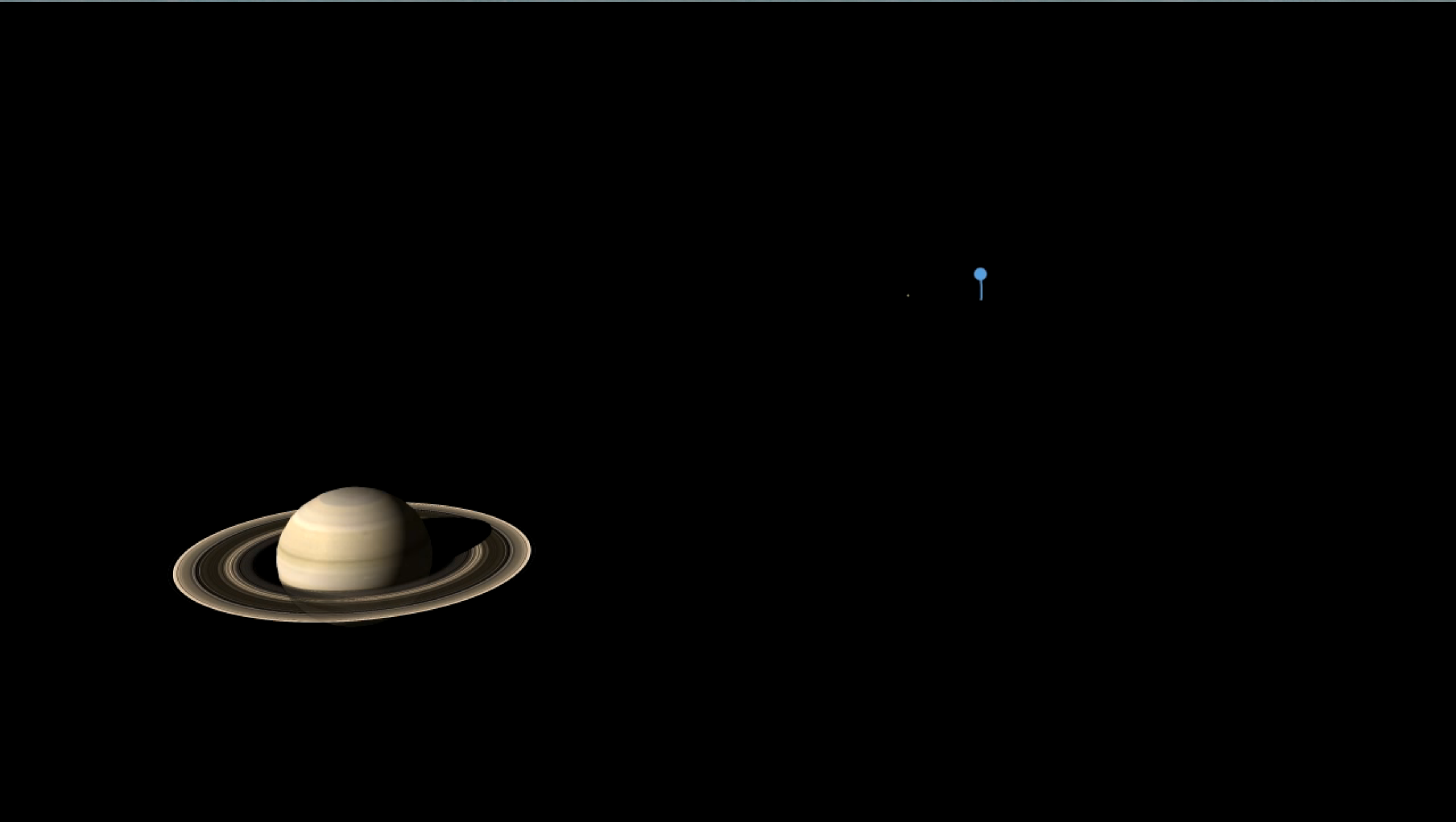
F-ring Orbits   Grand Finale Orbits   Final Impact Orbit

culminating with Saturn atmospheric entry on September 15, 2017

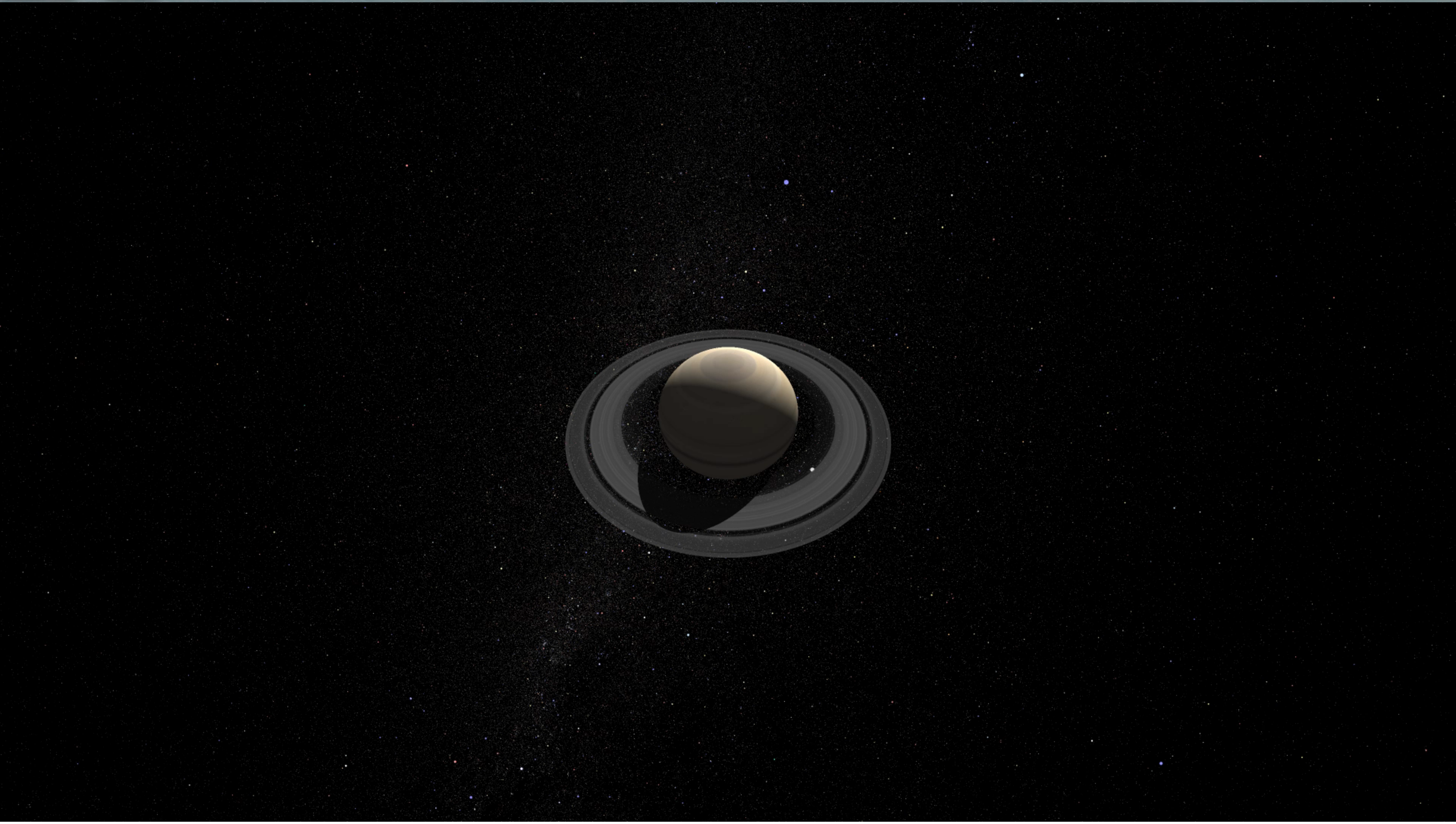
22 stable, highly inclined (62˚), short period orbits prior to Saturn impact

Ballistic in nature – **theoretically, no maneuvers required after T126**

Cassini Grand Finale



Grand Finale Ride Along



The Problem

Control the trajectory within 250 km from the reference path at all times

Why?

- Eliminates late sequence updates: non-standard process, compressed schedule to complete work, better if trajectory dispersions are known

How?

- Insert orbit trim maneuvers within proximal mission time span to meet objectives

Requirements

- Achieve Saturn atmospheric entry
- Ensure Cassini is safe from ring particle impact and above tumble density at periapsis
- Stay close to reference trajectory overall instead of focusing on flyby target
- Do not schedule maneuvers during occultations or within 24 hrs of Saturn periapsis
- Limit number of maneuvers to allow maximum time for science data collection

Use minimum number of maneuvers and propellant

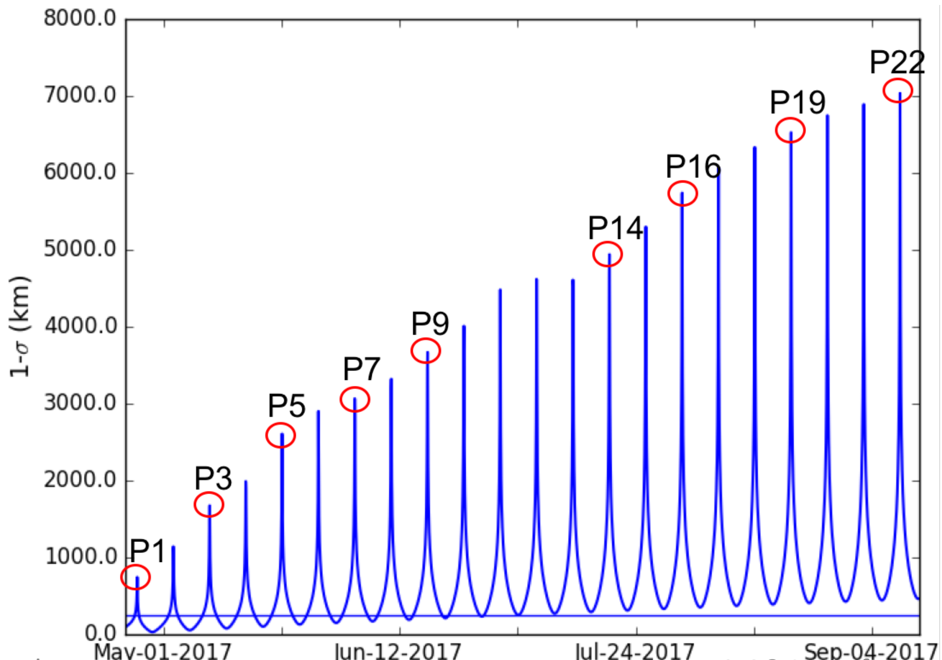
Sources of Uncertainties

Trajectory dispersions grow with time

- Ephemeris and masses of Saturn and its satellites
- Saturn's pole orientation
- Tracking station locations
- Earth's polar motion
- Maneuver execution errors

Sources of error

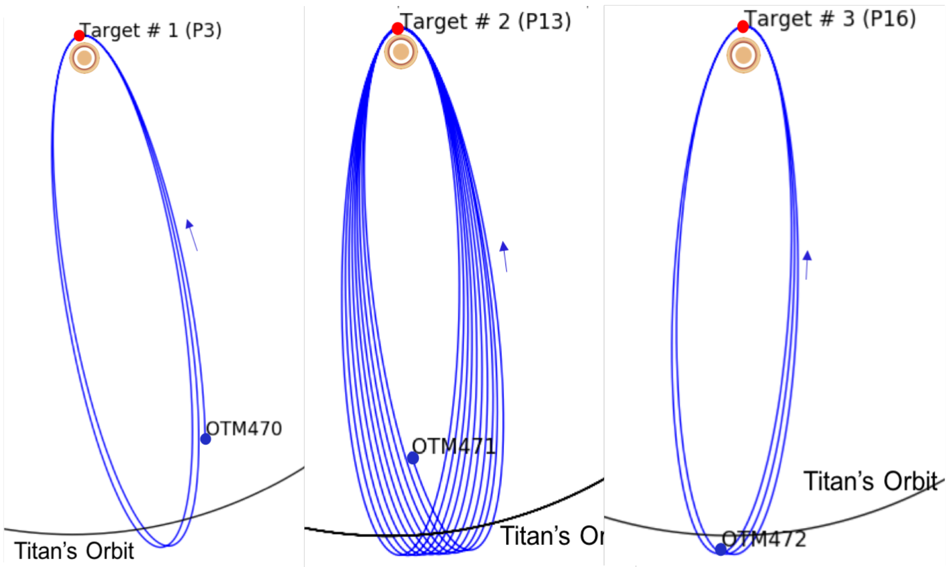
Dispersion Uncontrolled trajectory dispersions

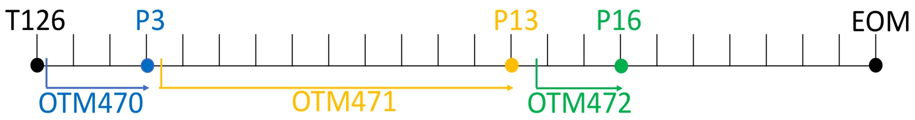


- 7,757 km along-track dispersion is equivalent to a periapsis timing difference of 226 seconds
- Peaks / troughs correspond to locations of periapsis / apoapsis
- Solid blue line represents the 250 km control threshold

Final Control Strategy: Prediction

Due to science observations and sensitivities to timing errors, the Cassini Project decided that only **P3, P14, P16** needed to be controlled and maintained under 250 km





OTM	Date	Target	DV (mean)	DV (1-sigma)	DV (99%)
470	24-Apr-2017	P3	0.59 m/s	0.38 m/s	1.74 m/s
471	10-May-2017	P13	0.14 m/s	0.10 m/s	0.44 m/s
472	15-Jul-2017	P16	0.06 m/s	0.04 m/s	0.19 m/s

Final Control Strategy: Prediction

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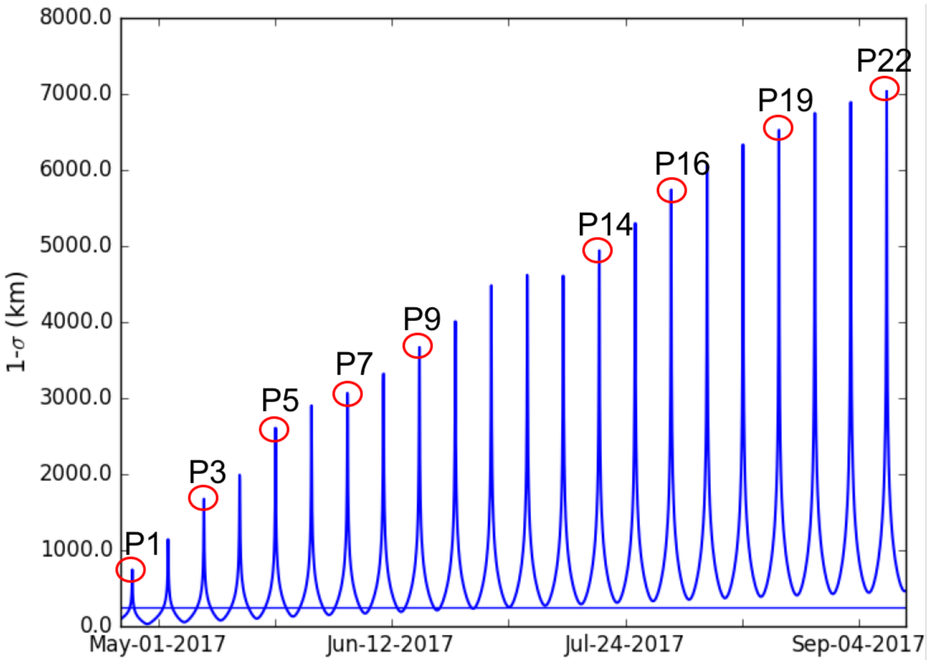
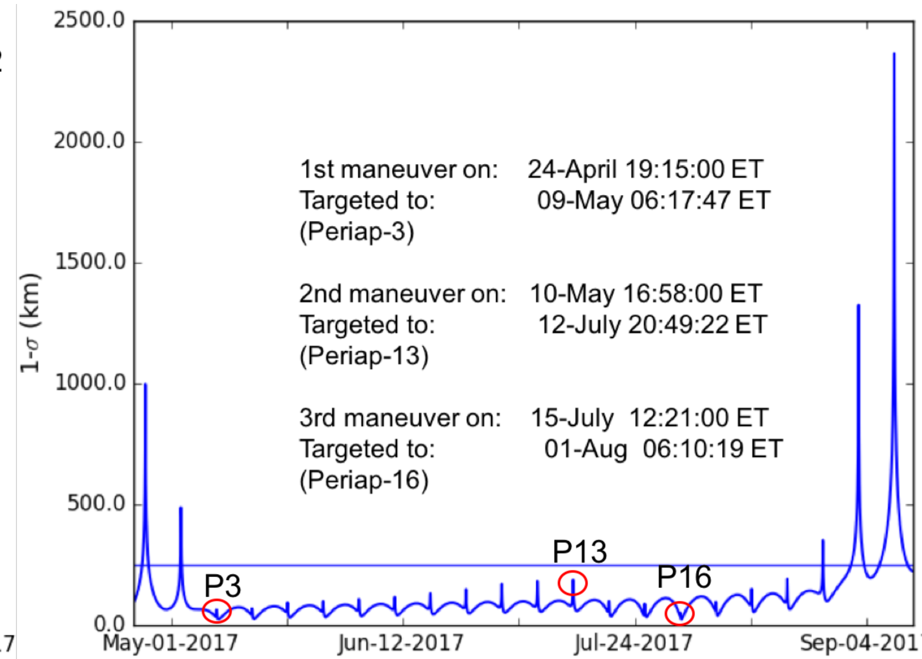


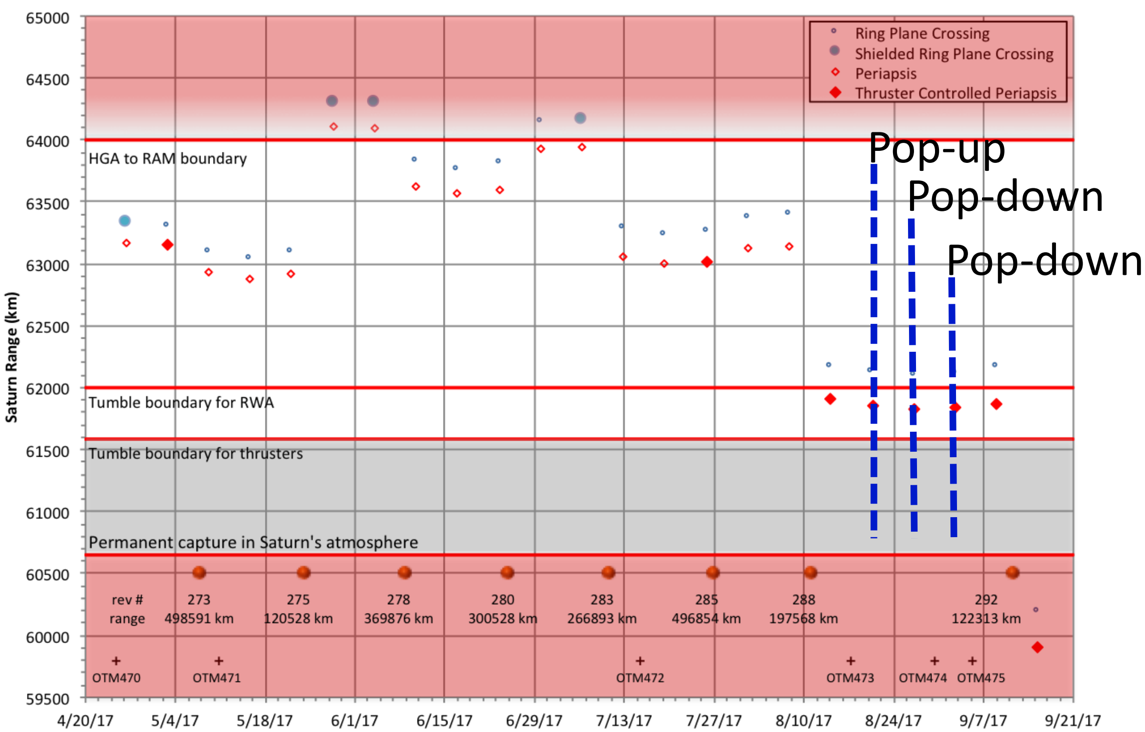


OTM	Date	Target	DV (mean)	DV (1-sigma)	DV (99%)	Position Dispersions
470	24-Apr-2017	P3	0.59 m/s	0.38 m/s	1.74 m/s	92.6 km @ P3
471	10-May-2017	P13	0.14 m/s	0.10 m/s	0.44 m/s	118.8 km @ P14
472	15-Jul-2017	P16	0.06 m/s	0.04 m/s	0.19 m/s	91.2 km @ P16

Contingency Maneuvers

Pop-Up and Pop-Down Maneuvers

OTM-473	17-Aug-2017	Pop-up
OTM-474	30-Aug-2017	Pop-down
OTM-475	05-Sept-2017	Pop-down



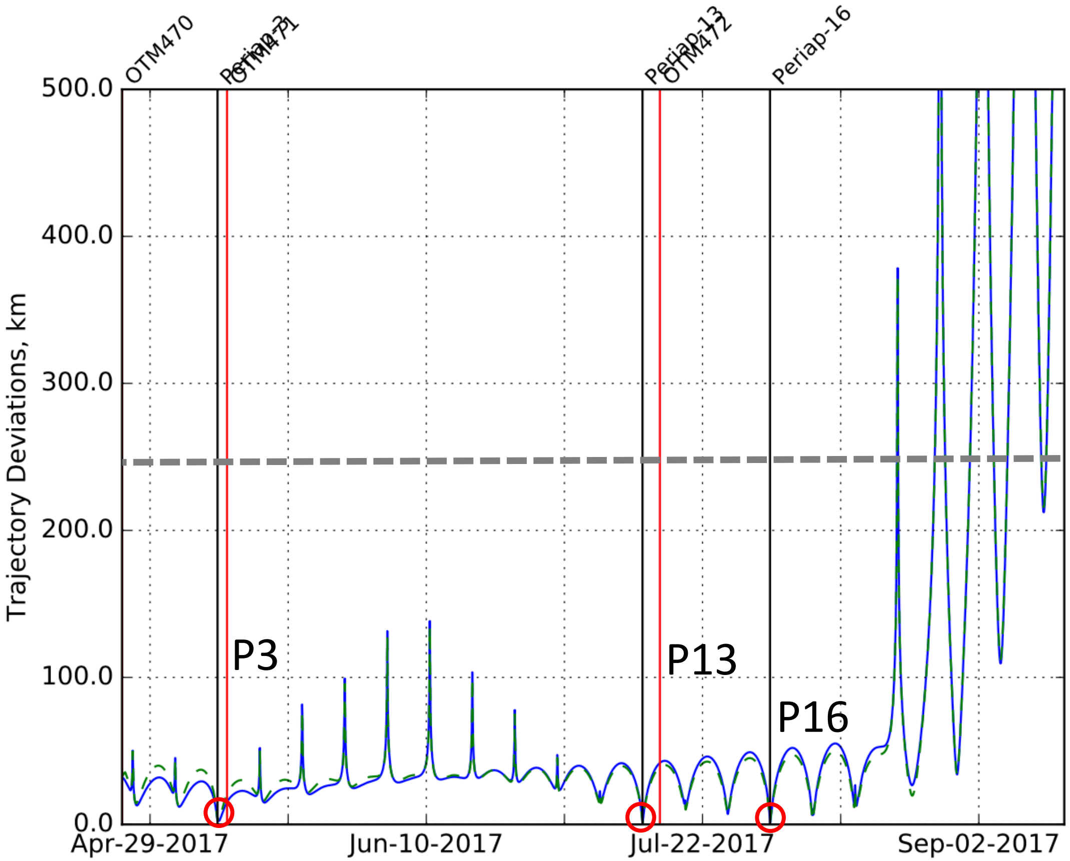
Two contingency scenarios:

- Atmosphere is thicker and denser than predicted: "pop-up" maneuver raises periapsis and maintains the SC safe from tumbling at P19 thru P22
- Atmosphere is thinner and lighter than expected: "pop-down" maneuver lowers periapsis altitude to allow better measurements of the atmosphere
- Maneuver estimates vary and depend on altitude change at periapsis
- Roughly: 250 km change ~ 3.5 m/s
- Expected to end the mission with 28 m/s of DV (1.1% of total mission DV)

Reality: From Titan-126 to P3

Last targeted Titan flyby miss: 312 m

ΔV	OTM-470	OTM-471
Predicted ΔV99	1.74 m/s	0.44 m/s
Implemented ΔV	0.156 m/s	0.020 m/s



- The navigation of the first three Grand Finale orbits went flawlessly
- Position deviation from reference trajectory at P3 was well below the predicted 1σ value of 92.6 km

Dispersions	@ P3
Predicted (1σ)	92.6 km
Actual	26 km

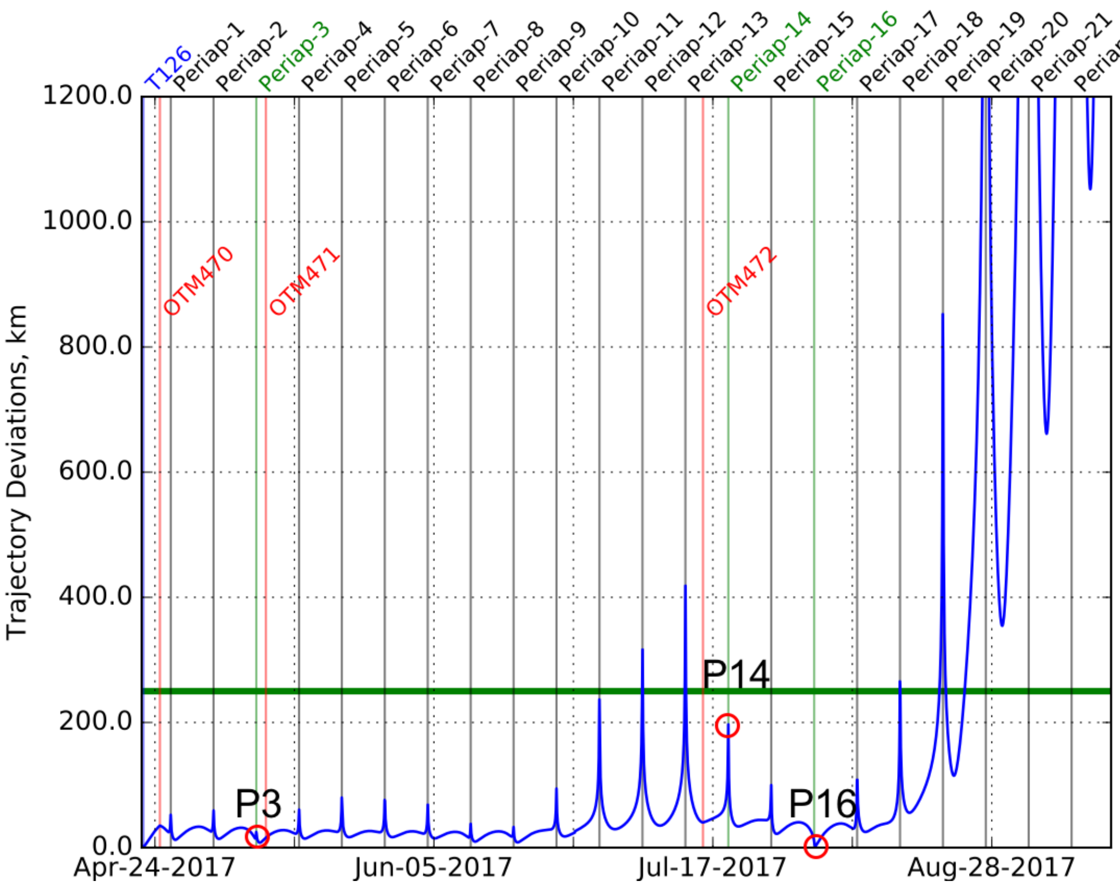
Reality: From P3 to P16

Navigation Challenges

- Small force predictions and SC attitude profile not available until 16-May-2017.
- Unexpected drag-like forces seen at many periapses for the first half of the Grand Finale, causing the time to consistently drift earlier at each periapsis passage.
- This drag-like effect vanished after P11 and the effect was reversed for later periapsis.
- The atmospheric density estimates varied from periapsis to periapsis during the final five revs, by a factor of 2.0 to 2.6 times larger.
- Although this variation did not present a control issue, it made it difficult to pin down a predicted loss of signal time (important for media relations).
- Measurements of performance: predicted vs designed maneuver magnitudes and predicted vs. achieved targeting accuracies.

Navigation Performance

Despite the challenges encountered, the implemented navigation strategy proved to be successful and end goal of maintaining position dispersions below 250 km at three specific periapses was met.



Event	Time Diff (Ref – Recon)	Event	Time Diff (Ref – Recon)
P1	-00:01.53	P12	00:10.00
P2	-00:01.81	P13	00:12.50
P3	-00:00.77	P14	00:05.77
P4	-00:01.82	P15	00:02.88
P5	-00:02.43	P16	00:00.12
P6	-00:02.46	P17	-00:04.07
P7	-00:02.10	P18	-00:08.44
P8	-00:00.93	P19	00:26.53
P9	00:01.63	P20	02:14.48
P10	00:04.24	P21	04:50.85
P11	00:07.18	P22	08:19.46

Navigation Performance

- OTM470 was considerably smaller than anticipated thanks to the last targeted Titan flyby accuracy (sub-km miss).
- Mismodeling effects caused larger deviations after P3 → design and implementation of OTM471 was practically unaffected.
- OTM472 magnitude ended up being higher than the predicted ΔV (1σ) value, yet smaller than the predicted $\Delta V99$ value.
- Overall, the total ΔV for the Grand Finale statistical maneuvers was on par with the 1σ predicted value: 0.400 m/s (predicted) vs. 0.321m/s (designed).

	ΔV	Predicted Mag.	Design Mag.
OTM470	mean 1-sigma 99%	0.59 m/s 0.38 m/s 1.74 m/s	0.156 m/s
OTM471	mean 1-sigma 99%	0.14 m/s 0.10 m/s 0.44 m/s	0.020 m/s
OTM472	mean 1-sigma 99%	0.06 m/s 0.04 m/s 0.19 m/s	0.145 m/s
TOTAL	mean 1-sigma 99%	0.78 m/s 0.40 m/s 1.94 m/s	0.321 m/s

Dispersions	**@ P3**	**@ P14**	**@ P16**
Predicted (1σ)	92.6 km	118.8 km	91.2 km
Actual	26 km	198 km	7 km

Summary of Findings

Maintain control of Grand Finale periapses under 250 km (1-sigma) w.r.t. reference trajectory using minimum ΔV

OBJECTIVE

Designed three statistical OTMs within proximal mission time span to meet objectives at three periapsis, total $\Delta V99 < 1.75$ m/s

DESIGN PROCESS

Implemented ΔV less than predicted ΔV (1σ)

Successful navigation strategy and OTM executions

Saturn atmospheric entry achieved

Position dispersions at periapsis controlled within 250 km

PERFORMANCE

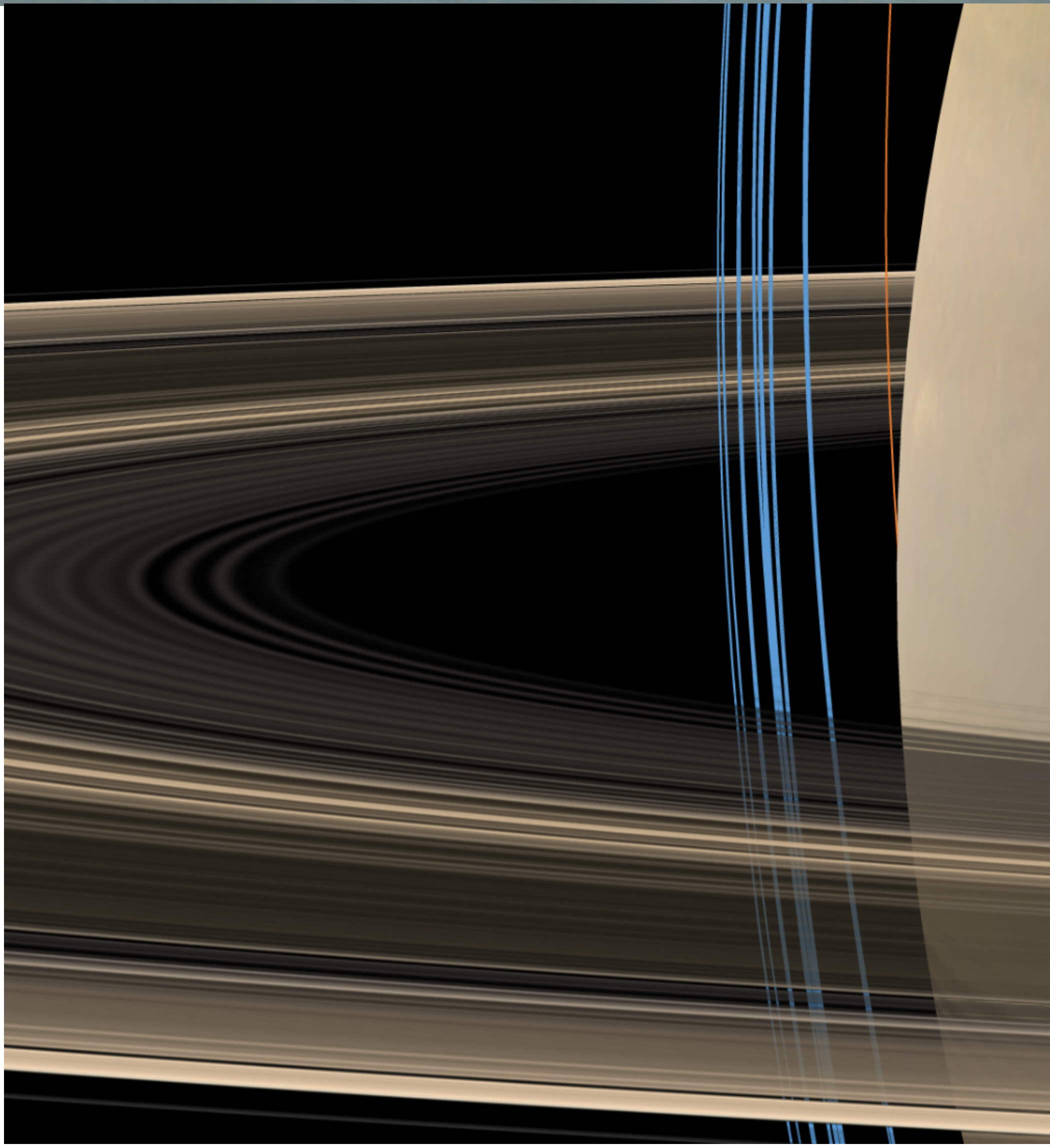
THE GRAND FINALE FROM AN ORBIT DETERMINATION PERSPECTIVE

Grand Finale Challenges and the Last 5 Revs

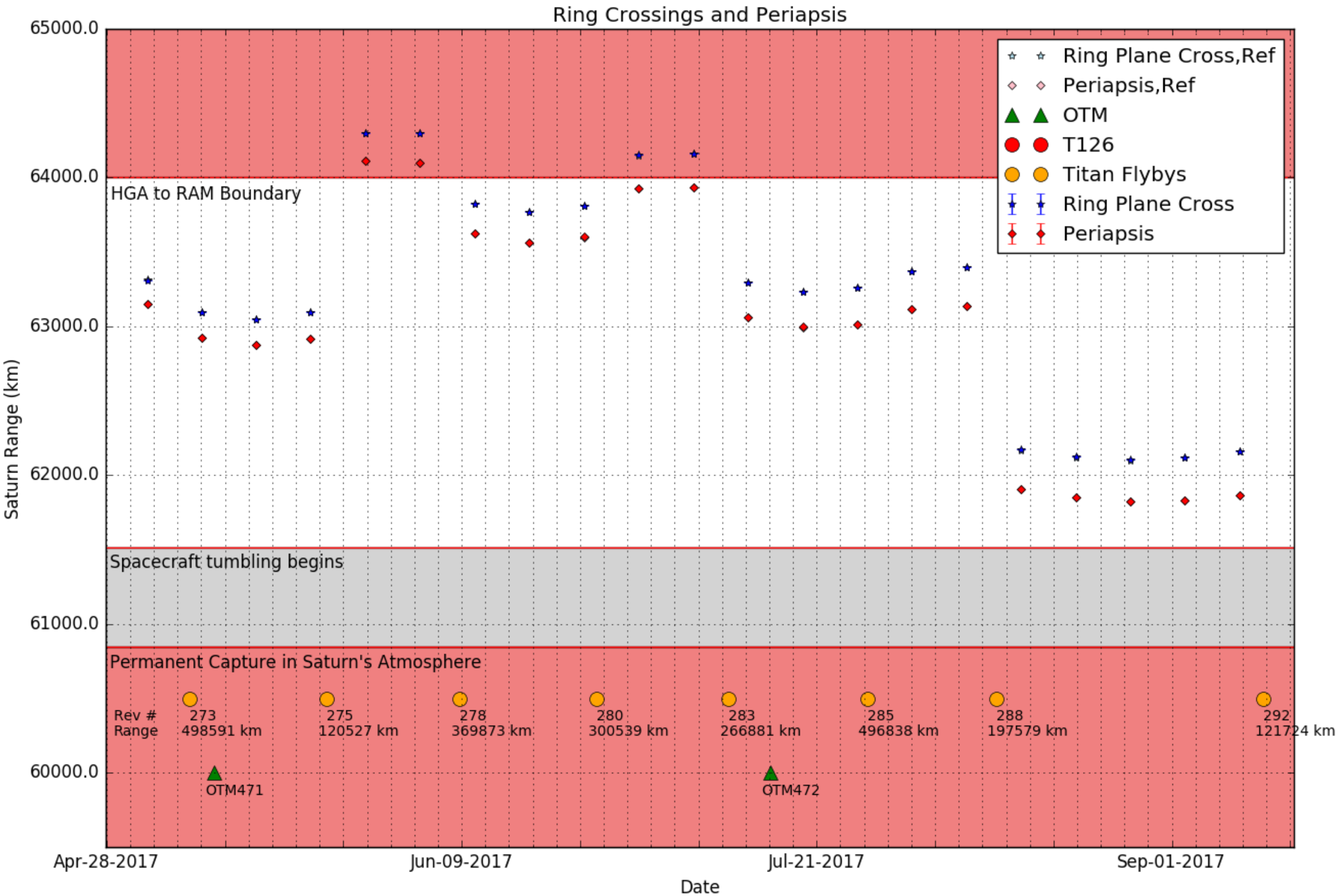
- On April 22nd, T126 brought Cassini's orbit periapse just inside the D-ring, making Cassini dive through the gap between Saturn and the rings every 6.4 days.

- The navigation requirements were relaxed due to the absence of satellite encounters and the stable inclined orbits.

- From a science request, three maneuvers were added in order to keep Cassini's trajectory dispersions below 250 km.



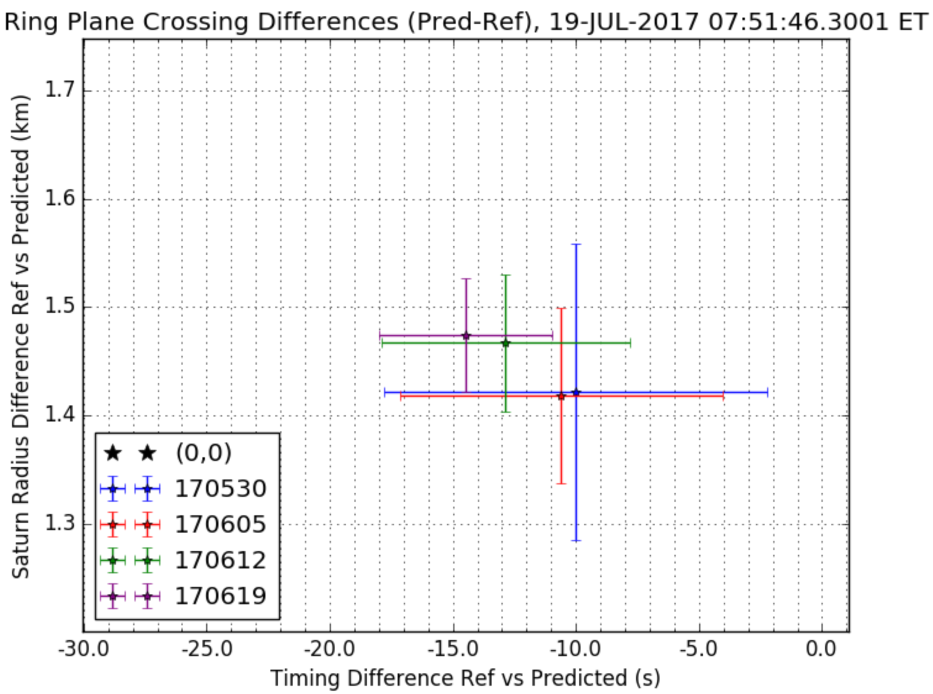
Saturn Crossings during the GF

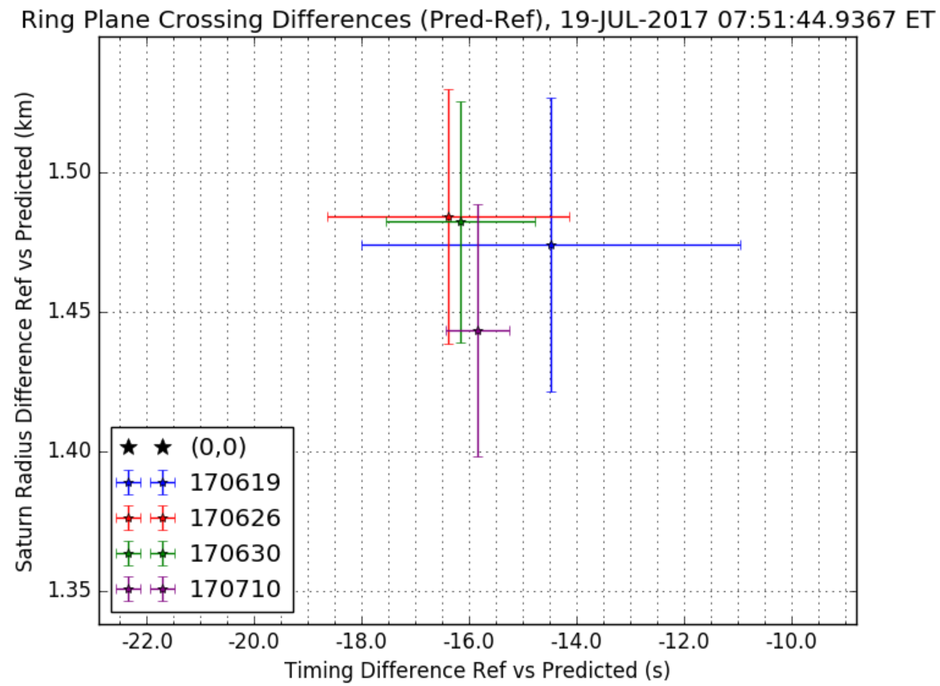


Saturn Crossings during the GF

- Timing drifts observed at Saturn periapses, compared to the reference trajectory.
  - Early assessments indicated some drag-like effects, where some fictitious Delta-V could be estimated between 0.2 and 0.5 mm/s.

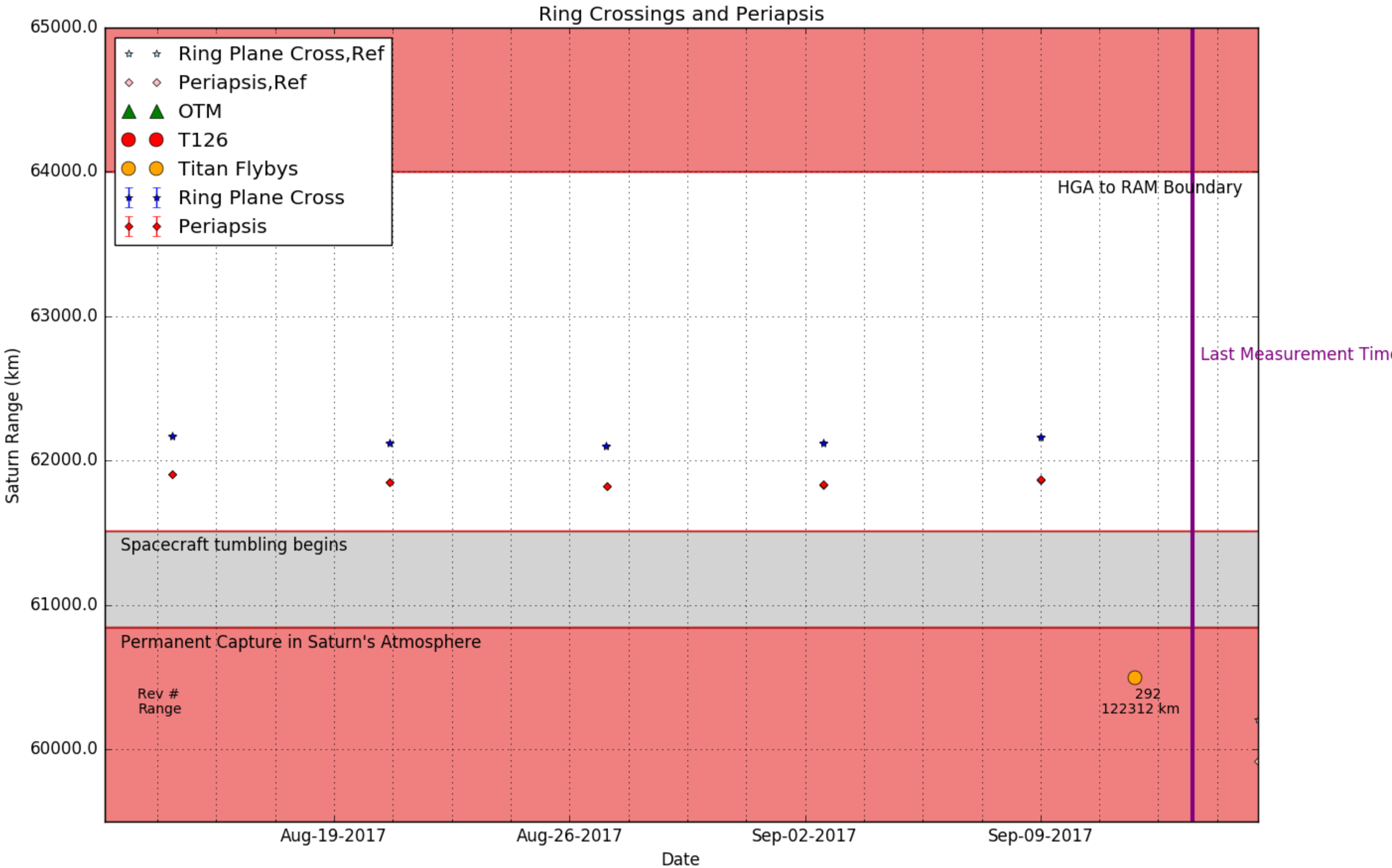
- High fidelity analyses are still ongoing to see if the unexpected Delta-V observed can be attributable to gravity or atmospheric mis-modeling.





Ring plane crossings between May 30th and June 19th 2017 (left), and between June 19th and July 10th 2017 (right).

The Last Five Revs



The Last Five Revs

- The finale was designed to graze Saturn's upper atmosphere at an altitude just below 62,000 km.

- After Cassini's first of those five dives, the atmosphere estimated to almost three times denser than the nominal model.
  - Pop-up maneuver and subsequent pop-down ones were canceled.

- The OD team's estimated Saturn's atmospheric density varied from 220% to 260%. Since the density itself is not estimated, this is shown through the Cassini spacecraft's drag coefficient.
  - Nominal CD is 2.1

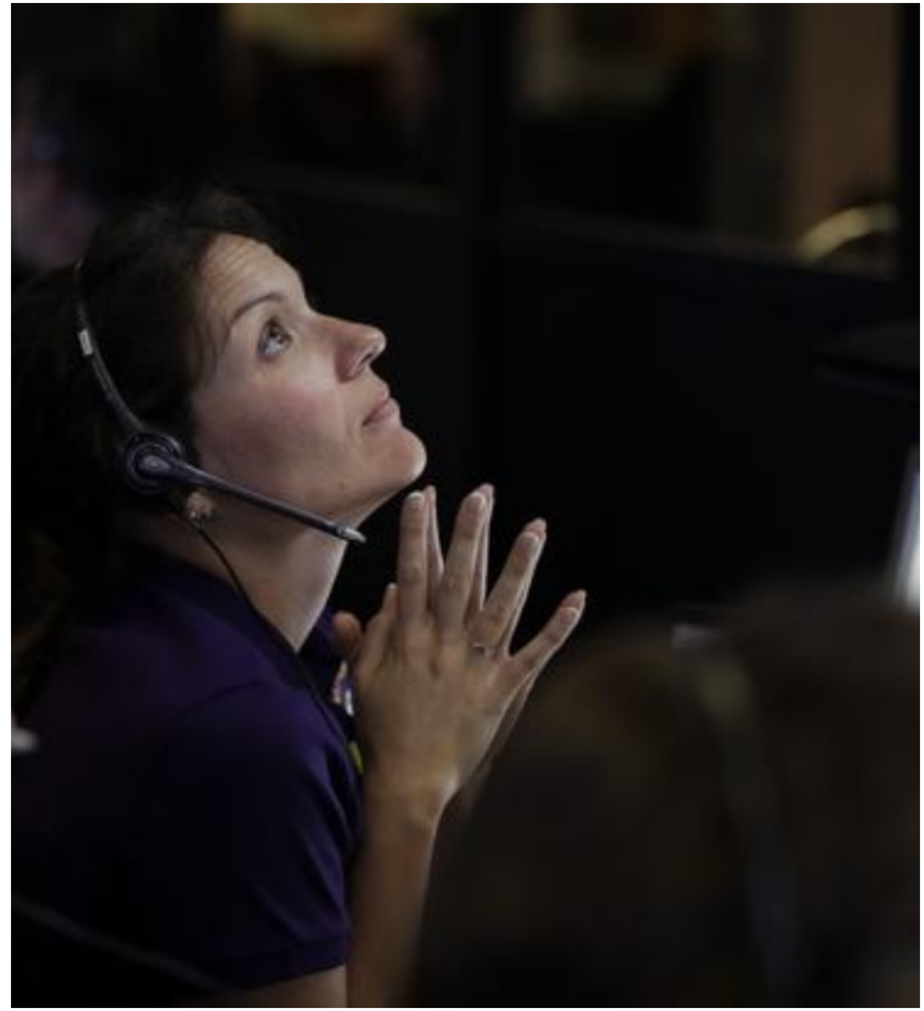
Saturn periapse times (ET)	Post-fit sigma	CD estimated value
14-AUG-2017 04:24:12	0.24	5.42
20-AUG-2017 15:24:09	0.17	5.76
27-AUG-2017 02:19:19	0.12	4.84
02-SEP-2017 13:14:09	0.16	5.34
09-SEP-2017 00:10:54	0.20	5.34
15-SEP-2017 10:55:16	0.48	4.98

The Grand Finale was Spectacular!

- The Cassini's trajectory was the most complex trajectory flown in the history of spaceflight, and the mission's final year gave everyone great wonders on all levels.
- For the first time, Cassini grazed the rings and the planet at close distances never achieved before.
- It returned breathtaking images, and the data gathered will feed science analyses for at least another decade.
- One takeaway from the Cassini end of mission is to never underestimate unknown events
  - 3-s change can still happen even after 13 years of mission operations.
- The Cassini mission is currently working on a full mission reconstruction, from July 1st 2004. The reconstructed trajectory will be presented at the Space Operations Conference in May 2018.
- The official loss of signal time on September 15 for the Attitude and Articulation Control Subsystem (AACS) predicted altitude, and from the last telemetry and X/S band Doppler data received.

	UTC ERT epoch	Altitude (km)	Range (km)	Latitude (deg)
AACS prediction	11:55:16	1,397.3	61,484.6	9.36
X telemetry	11:55:18	1,384.6	61,474.1	9.30
X carrier	11:55:37	1,266.8	61,375.6	8.77
S carrier	11:55:44	1,224.3	61,340.1	8.58

THE MORNING OF THE GRAND FINALE



The Morning of the Grand Finale

Mission Control Room at JPL